CONSTRUCTING A CONCEPTUAL MODEL LINKING DRIVERS AND ECOSYSTEM SERVICES IN PIEDMONT STREAMS

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Abstract. Under rapid land use change, high demand on freshwater ecosystem services, and a growing appreciation for the value of functioning ecosystems, the Appalachian Piedmont has developed a multi-million dollar stream restoration industry. A comprehensive understanding of ecosystem structure, function, and process is necessary to effectively plan, design, monitor, and adaptively manage these projects. Furthermore, funding agencies must justify their restoration investments in terms of environmental benefits and ecosystem services provided by a single project as well as a suite of projects. To this end, this paper presents a Piedmont stream conceptual model mapping common system drivers and stressors to the ecosystem services they affect. We focus only on the supply of ecosystem services and not demand for those services. This paper will (1) discuss the role of conceptual modeling in stream restoration, (2) present a suite of conceptual models for Piedmont streams with increasing levels of detail, (3) briefly demonstrate application of the these models, and (4) highlight areas of need for future model development activities.

INTRODUCTION

According to Fischenich (2008), “Conceptual models are descriptions of the general functional relationships among essential components of an ecosystem.” These models not only tell the story of ‘how the system works’ but also help to facilitate communication amongst interdisciplinary teams, identify cause-and-effect relationships, diagnose drivers and stressors, brainstorm alternative actions, and compare the costs and benefits of those actions (Fischenich 2008). In this paper, a conceptual model of Piedmont stream ecosystems is presented which can be utilized to inform stream restoration, water management, land use development, and other water resources decision-making in the region.

A regional approach based on physiographic characteristics, rather than political boundaries, is best suited for conceptual model development for several reasons. First, by stratifying based on physiographic boundaries, natural variability is significantly reduced in regards to valley and stream slopes, soil properties, geology, climate, land use, and vegetative community types. Second, a regional conceptual model can be utilized in many projects throughout the area, and thus, provides a source of efficiency in project planning or model development.

The Piedmont ecoregion extends from central Alabama northeast almost to the Virginia-Maryland border and is bound by the Appalachian Mountains and Blue Ridge to the northwest and the Atlantic Coastal Plain to the southeast (Figure 1). Elevations range from approximately 152 to 457 meters above sea level (500 to 1500 feet).

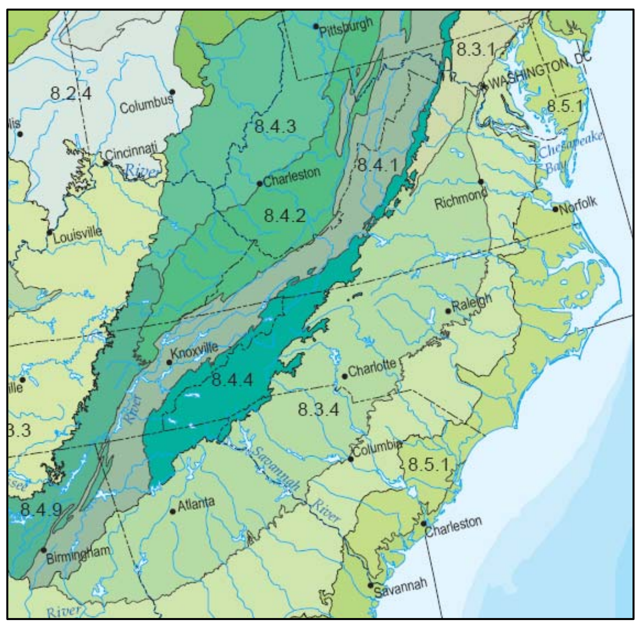

Figure 1: Level III Ecoregion (CEC 1997). The Piedmont is shaded in light green and labeled as 8.3.4.

Piedmont streams have been adversely affected by land use practices spanning nearly two centuries. Historical cotton farming practices of the 1800s and early 1900s induced significant erosion such that, in much of the Piedmont, the original topsoil has eroded away exposing red clay sub-soils (Jackson et al. 2005, Trimble 2008). At

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14. ABSTRACT
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the turn of the 20th century, a program was initiated to improve drainage and "reclaim" agricultural lands in Georgia by dredging and channelizing streams (Barrows et al. 1917), which resulted in further channel incision and erosion. In the last 50 years, the Piedmont has undergone massive population growth and urbanization, which has myriad impacts on aquatic ecosystems (Wenger et al. 2009). Future impacts from continued urban build-out are poorly understood, and potential effects of climate change further complicate environmental decision-making in the region.

In contrast to these threats, Piedmont streams provide many ecosystem goods and services ranging from assimilation of waste to wildlife observation. Furthermore, Southeastern streams exhibit high aquatic biodiversity with many endemic species (CBD 2010).

As a consequence of the many threats on and benefits of these stream ecosystems, stream restoration and management have become sources of major economic investment throughout the region (Sudduth et al. 2007). Although significant resources have been focused on the improvement of these streams, a comprehensive framework for accounting for the benefits of these efforts has not been addressed. Herein, we present a conceptual model of Piedmont stream ecosystems which documents the effects of drivers and stressors on the goods and services provided by these ecosystems. Complete documentation and presentation of this model is beyond the scope of this paper; thus, this paper intends only to present a preliminary version of the model and how it can be adapted and applied for specific projects.

A FRAMEWORK FOR CONCEPTUAL MODELING

The general approach to conceptual model development was to: (1) develop an overarching framework linking drivers and stressors to ecosystem goods and services, (2) populate that framework with Piedmont-specific elements, and (3) use peer-reviewed literature to document the mechanisms linking elements in the conceptual model. To accomplish this task, the model was developed in a workshop with subject matter experts representing a variety of disciplines including stream and riparian ecology, biogeochemistry, hydrology, geomorphology, engineering, and project planning. This workshop was convened in June 2010 and included a variety of agency and academic personnel from across the region.

The generalized framework for conceptual model development (Figure 2) demonstrates how the provision of ecosystem goods and services is affected by ongoing social, physical, and ecological processes in a given stream system. The following sections explain each of these organizational categories in greater detail, but it is instructive to briefly review the overall flow of the conceptual modeling framework. The social context determines the drivers and stressors (e.g., local economic growth leading to land development). These drivers and stressors influence four primary physical and chemical state conditions (e.g., construction of a flood control dam to protect developed land which affects connectivity). These states influence local biota by altering population processes (e.g., longitudinal disconnection from downstream source populations by the dam) which in turn controls biodiversity. All of the above influence the provision of ecosystem goods and services (e.g., reduced stream fishery health), and lastly, the provision of ecosystem services feedbacks onto the social context (e.g., use of the flood control dam for water supply provision). Connecting each of these elements of the model are numerous physical, chemical, and ecological processes and patterns which are specific to a given set of drivers and services (See examples below).

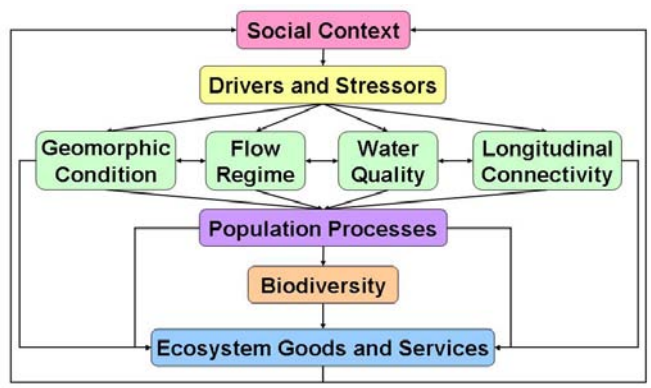

Figure 2: Generalized framework for developing a Piedmont stream conceptual model.

ELEMENTS OF THE CONCEPTUAL MODEL

Although the general framework presented above can be useful in structuring a conceptual model, it does not provide a Piedmont-specific set of issues to be included in the conceptual model. Thus, the workshop team compiled a list of these conceptual model elements for each category described in Figure 2. A brief description of each component of the conceptual model is summarized in the following paragraphs and Figure 3.

Social context describes the socio-economic, cultural, demographic, and political systems that influence water resources decisions. These pressures come in many forms varying from public opinions and attitudes to legal constraints and political jurisdictions to management actions intended to counteract degradation (e.g., conservation or restoration). Developing a comprehensive list of potential social influences is not the intent of this conceptual model, but the workshop team opined it was important to explicitly acknowledge that all drivers, stressors, and decisions regarding Piedmont streams are fundamentally influenced by the social system in which they reside.

Herein, we conform to the definition of Fischenich (2008), who describes drivers as “physical, chemical, or biological factors of natural or human origin” and use this term synonymously with stressors. Figure 3 provides a summary and classification of common drivers and stressors observed in the Piedmont. As described above, historic and current land uses in the Piedmont are two drivers that play a significant role in the condition of Piedmont streams, but other stressors such as resource extraction (e.g., mining), ecosystem engineers (e.g., beavers), infrastructure (e.g., dams), and climate change should also be considered.

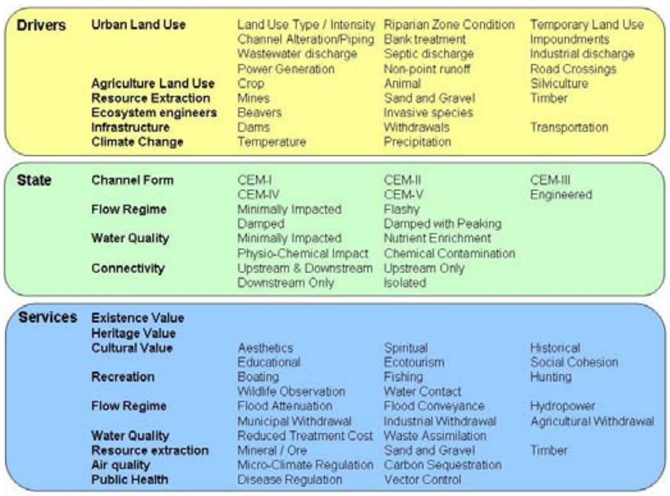

Figure 3: Elements for inclusion in conceptual model.

Although these drivers and stressors can influence streams in countless ways, ecosystem condition within the Piedmont can be summarized by a relatively small number of “functional states” characterized by geomorphic condition, flow regime, water quality, and longitudinal connectivity (Figure 3). What follows is a proposed categorization of each of these functional states which attempts to represent the system in terms of dominant processes. The channel evolution model (CEM) is a well-supported model for the geomorphic evolution of alluvial channels undergoing changes in discharge or sediment regime (Simon 1989, Watson et al. 2002). The CEM proposes five stages of evolution (I. a pre-disturbance condition, II. channel degradation, III. channel widening, IV. aggradation, and V. alternative dynamic equilibrium) to which we add a sixth state, engineered channels (e.g., concrete or piped). Although a stream’s flow regime is characterized by many variables and processes (e.g., magnitude, frequency, duration, etc.), these combine in similar ways throughout the Piedmont to generate four general classes of flow regimes: (1) a “minimally-impacted” condition, (2) a “flashy” system characterized by higher peaks and reduced base flows, (3) an infrastructure-induced “damped” flow regime with reduced peak flows and higher base flows, and (4) a damped condition with significant within-day variability from hydro-peaking or water withdrawal. Additionally, water quality cannot be summarized by a single variable or process; however, water quality variables often co-occur and four proposed state conditions are proposed as follows: (1) minimally impacted, (2) nutrient enriched, (3) physio-chemical impacts such as temperature and dissolved oxygen which are often a result of point source effects, and (4) chemically-contaminated. Lastly, longitudinal connectivity affects the delivery of mass, energy, and organisms throughout a system (Pringle 2003) whether they be positive or negative effects (e.g., accessibility for invasive species, Jackson and Pringle 2010) and streams can be coarsely divided as being connected: (1) upstream and downstream, (2) upstream only, (3) downstream only, or (4) isolated. This classification is intended not to imply that other states cannot exist, but instead that dominant forces in a system can often be reduced into one of these simplified state conditions.

Through a variety of mechanisms, these state conditions influence local biota through demographic processes such as survival, reproduction, and colonization. The effects on these population-level processes influence community dynamics and local biodiversity. Although biodiversity is not explicitly an ecosystem process or service, it does influence system dynamics. For instance, the resilience of a stream to provide flood attenuation services may be directly connected to the capacity of multiple forms of riparian vegetation to recover after a flood.

“Ecosystem services are the benefits people obtain from ecosystems” (MEA 2005). Thus, ecosystem goods and services provide a logical means for measuring and trading-off the value or benefit of a particular management action (e.g., stream restoration). Many sources have offered lists of ecosystem services and reviewed techniques for quantifying and/or monetizing these services (e.g., MEA 2005, Brown et al. 2007). Figure 3 presents a condensed list of ecosystem goods and services typically provided by Piedmont streams. We focus only on the provision of ecosystem services, but ecosystem services are only provided if there is a demand for a given service, a dimension isolated from this discussion. These potential ecosystem services could be used in a variety of ways such as metrics for trading-off the advantages of restoration alternatives or communicating the benefits of restoration actions to funding agencies, stakeholders, or the public at large.

APPLYING THE CONCEPTUAL MODEL

Thus far, we have presented a general framework for conceptual modeling and a list of elements that should be included in a Piedmont stream conceptual model. Although these alone may be sufficient for certain venues (e.g., communicating with the public). Other applications

of a conceptual model (e.g., restoration design) may require additional detail regarding governing processes or mechanisms. As such, this section provides two example applications of the conceptual model which link the same driver, channel straightening, to two different ecosystem services, flood attenuation and existence value. A conceptual model should not reflect all ongoing processes, but instead processes relevant to the questions at hand. As such, the reader should notice that although the drivers are the same, the effected state conditions and resulting processes influencing the ecosystem service differ.

Flood attenuation is a service that provides reduction or "balancing" of flood events by storing surface water in floodplains and riparian zones, thus releasing surface water slower over a longer period of time. Two states affect flood attenuation, geomorphic condition and flow regime (Figure 4). Geomorphic condition alters the accessibility of the floodplain (Burke 1990, Pruitt 2001) as well as bed form diversity and coarse woody debris (CWD) loading. Flood storage also depends on the condition of the riparian zone (e.g., open field v. dense forest) and the event magnitude required for floodplain inundation, both of which are related to the flow regime. Consequently, adequate upstream storage volume and hydraulic roughness in the stream channel and associated floodplain function interact to attenuate or abate the risk of downstream flood events.

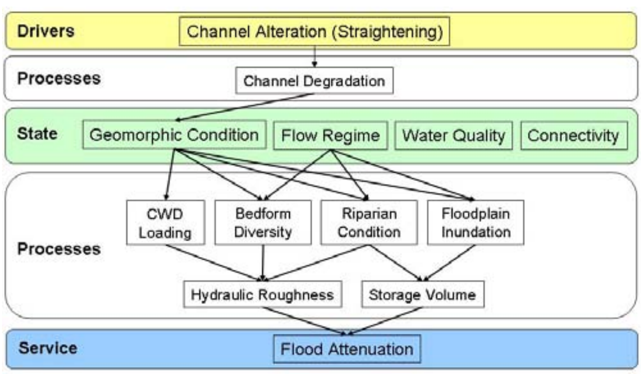

Figure 4: Application of the conceptual model: Effects of channel straightening on flood attenuation.

Existence value of a fish is dependent upon its persistence through time. Take for example a hypothetical fish of concern (e.g., a threatened benthic fish). Similar to flood attenuation, the persistence of this taxon is influenced by the state or condition of the channel form and flow regime. However, the status of water quality and longitudinal connectivity also affects the long-term health of this species (Figure 5). The above four states have a bearing on three major categories of population processes: reproduction, survival, and colonization. While reproduction may be influenced by the availability of specific substrates or bedforms, survival may be determined by many more factors such as available habitat (e.g., substrate, bedform diversity, and vegetative cover), appropriate water quality conditions (e.g., temperature, dissolved oxygen, pH, and turbidity), and the availability of autochthonous or allochthonous food sources, which are dependent on longitudinal connectivity. Lastly, following a disturbance event such as a drought or a flood, longitudinal connectivity to other source populations may be critical for repopulating a given reach.

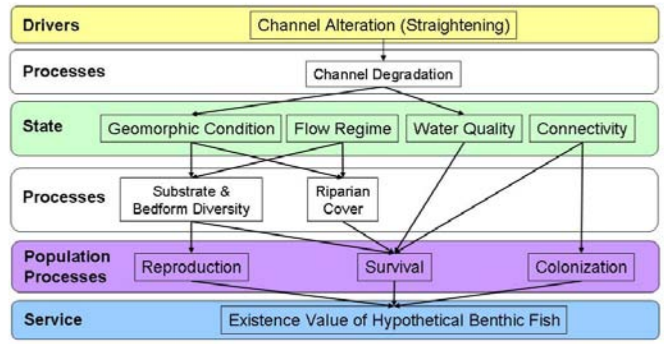

Figure 5: Application of the conceptual model: Effects of channel straightening on existence value associated with persistence of a hypothetical benthic fish.

These applications are merely intended to provide examples of how the general conceptual model could be expanded to include more detailed information. It is, however, important to note that these examples focus on supply of ecosystem services and that valuation of that service is dependent on demand, a dimension which has been ignored in this discussion.

DISCUSSION

Herein, we have presented a conceptual model of Piedmont streams with the intent of connecting drivers and stressors to ecosystem goods and services. Different forms of the conceptual model express increasingly detailed information, and an appropriate level of detail should be used depending on the venue (e.g., public meeting v. scientific documentation). This model could be used as a template for a project-specific conceptual model that is adapted to local drivers and emphasizing ecosystem services that are most valued at the local level.

The importance of making the connection and understanding the ecological linkages between drivers and stressors, state conditions, and multiple ecosystem services cannot be over emphasized. Recognition of the correspondence between state conditions and ecological processes allows for restoration designs that are supportive of multiple ecosystem services. For example, successful restoration of recreational fishing enhances other ecosystem services such as existence value, water treatment cost, and wildlife observation.

Finally, this paper has presented a preliminary version of the conceptual model, and future activities for increasing the model's utility are outlined below.

- Although the general framework (Figure 2) and 'pick-list' of model elements (Figure 3) provide a starting point for users to develop their own conceptual models, the workshop team plans on providing additional mapping of drivers and stressors to goods and services along with accompanying documentation.
- Development of a web-based suite of conceptual models would transition these models into application more quickly and assist model users with tailoring the model to their application of interest.
- The models will be beta-tested on restoration projects in the region. Thus, providing an example of how a regional model may be tailored to fit local needs.

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